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METALLURGICAL INVESTIGATIONS ON BIMETALLIC WELD JOINTS IN AUSTENITIC/FERRITIC STAINLESS STEELS FOR PAPER-PULP INDUSTRIES

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ABSTRACT

This research article investigated metallurgical and weldability properties of AISI 316L and AISI 430 stainless steel weld-joints obtained by pulsing current gas tungsten arc welding (PCGTAW) process by employing ERNiCr-3 and ER2209 filler wires. Microstructural investigations witnessed the migrated grain boundaries at the weld zone of ERNiCr-3 and coarsened grains were very minimal at ER2209 weldments. This study is highly in demand in paper and pulp industries and successfully addressed the choice of fillers and detailed study has been carried out to analyze the structure-property relationships of these weldments using the combined techniques of scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) analysis.

***KEYWORDS**: AISI 316L and AISI 430 Stainless Steels, ER 2209 and ER NiCr-3 Fillers & Microstructural Characterization*

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Original Article

1. INTRODUCTION

Dissimilar metal welding is not only minimizing the volume of expensive materials used in these bi-metal joints and lower amounts of Nb and Mo elements were dissolved in the matrix to the extent possible and remaining elements segregated as secondary phases. [1]. Welding of dissimilar metals is highly challenging and cumbersome task as compared to the similar metal welding owing to the differences in chemical composition and the coefficient of thermal expansions of the base metals employed [1-4].

Inconel 625 is a high-chromium, high-molybdenum, nickel-based super alloy, widely used in form of bulk, weld-overlay, and plasma-sprayed coatings for high-temperature applications in many corrosive environments: gas turbines, waste-fired boilers as well as pulp and paper industries. Similarly, austenitic stainless steels have a wide range of applications in chemical, petrochemical industries and power engineering sectors due to the combined properties of strength and corrosion resistance. AISI 316L has typical advantages compared to the other grades of stainless steel such that they are not prone to sensitization at elevated temperatures. Bimetallic combinations of Inconel 625 and austenitic stainless steels were employed by NASA [5] for the construction of subscale boilers. These boilers were tested to investigate the boiling stability after being operated with boiling NaK for 792 hr at temperatures from 700 to 750°C. Xiaowei Wu et al.[6]. Reported the typical advantages of brazed joints of Inconel and austenitic stainless steel, which were developed to withstand high

temperatures and widely designed for aero-engine hot section components. Further various researchers [6, 7] reported that the joints of these combinations could be employed in oil-refinery converters where the temperature can reach up to 1050°C and the atmosphere is highly carburizing and oxidizing. Austenitic stainless steel is most prevalent material used in high-temperature applications which would be a good alternative for Inconel. Hence welding techniques were adopted to join Inconel series and cost -effective stainless steel grade to accrue better mechanical properties [7-9].

Solidification/liquation cracking, ductility - dip cracking (DDC) and precipitation of Cr-carbides in the weld are the major problems usually encountered during welding of dis-similar alloys [10]. Patterson et al. [11] observed the solidification cracking at the weld zone during the autogenous gas tungsten arc welding of Inconel 625 and 304L stainless steel. Studies made by Devendranath Ramkumar et al. [12] on the dissimilar joints of Inconel 625 and AISI 304 clearly showed the precipitation of chromium carbides at the HAZ of stainless steel. Due to the presence of higher amounts of Nb content in the filler metal, enriched segregation was observed at the HAZ of Inconel 625. Also, the authors strongly believed that the effects of secondary phases were slightly lowered on employing PCGTA welding.

Du Pont et al. [10] reported that the selection of welding process and process conditions also have an influence on cracking susceptibility. Further, the authors recommended the use of low heat input welding processes and conditions which would be favorable in avoiding such types of cracking. Jeng et al. [13] reported the precipitation of Cr-carbides at the inter-dendritic regions could be mitigated by using Nb added filler wire. Devendranath et al. [14] investigated the bimetallic joints of Monel 400 and AISI 304. The authors claimed that the use of E309L filler would result in the formation of secondary phases which could deteriorate the metallurgical and mechanical properties of the weldments. Further, the authors recommended that the use of the pulsed mode of GTA welding process for eliminating the formation of these phases. Several researchers reported on the advantageous aspects such as improvement in strength and ductility while employing the pulsed current GTA welding on different materials [12, 15-17]. Devendranath et al. [18] investigated the comparative analysis on the CCGTA and PCGTA weldments of Inconel 718 and AISI 316L using ER2553 and ERNiCu-7 fillers. The authors concluded that PCGTA welding aided in controlling the deleterious laves phase and also facilitated for enhanced mechanical properties.

It is evident from the literature, the application of joining AISI 316L and AISI 430 is wide and it requires thorough analysis in terms of the joint's performance in room temperature conditions. The present study features the weldability and metallurgical properties of these bimetallic joints obtained by pulsing current GTA welding techniques by employing ER2209 and ERNiCr-3 filler metals. The welded trials were characterized for the optical macro/micrograph, SEM/EDS analysis to understand the metallurgical behavior. The results elucidated in this paper will be highly useful to paper and pulp manufacturers operating with these bi-metallic joints.

Table 1: Chemical Composition of Base and Filler Metals

Chemical Composition (% weight)							
Base / Filler Metal	**C**	**Cr**	**Ni**	**Mn**	**Mo**	**Fe**	**Others**
							Co - 0.022; Cu - 0.01; Al - 0.003; Ti -
AISI 316L	0.028	16.74	10.2	1.26	2.11	Rem.	P -0.030; S -0.01; Si - 0.25
AISI 430	0.04	16.27	0.15	0.37	0.01	Rem.	Co - 0.02; Cu - 0.015; Al - 0.003; Ti -
ER2209	0.022	23.50	7.5	1.5	3.12	Rem.	P -0.033; S -0.01; Si - 0.27
ERNiCr-3	0.085	21.58	67.2	2.52		Rem.	Ti - 0.74; Cu - 0.5; Si - 0.014; P 0,02;
							S - 0.4; Nb - 2.22

Table 2: Process Parameters Employed in PCGTA Welding of AISI 430 and AISI 316L

Process	Filler	Voltage (V)	Current (A)	Base Current I_{base}(A)	Peak Current I_{peak}(A)	Frequency HZ
PCGTAW	ERNiCr-3	12.5		88-90	155	5
PCGTAW	ER2209	12.9		78-82	150	5

2. EXPERIMENTAL DETAILS

2.1. Parent Metals Welding Procedure

The as-received base metals employed in these studies were AISI 430 and AISI 316L. These plates were joined by PCGTA welding processes employing two different filler metals such as ER2209 and ER-NiCr-3. The chemical composition of the base and filler metals employed in this study is represented in Table 1. The base plates were cut and machined to the dimensions of 155 mm long × 50 mm wide × 4 mm thick using wire-cut electrical discharge machining (EDM). Standard butt configurations (single V-groove having a root gap of 1-2 mm, size land of 1mm and included an angle of 80°) were employed on the plates before welding. The process parameters employed for joining these dissimilar metals were obtained based on the existing open literature as well as confirmed by the bead on plate welding and shown in Table 2. These dissimilar weldments were subjected to different metallurgical and mechanical tests to investigate the structure-property relationships.

2.2. Characterization of Weldments

After welding, the dissimilar weldments were investigated for any flaws using gamma-ray NDT technique. Ensuring to the results, these weldments were cut to coupons of different dimensions using wire-cut electrical discharge machining (EDM) process for performing various metallurgical examinations to arrive at the structure-property relationships. Coupons of the transverse sections of the welded samples having the dimensions of 30 mm × 10 mm × 4 mm known as “composite zone” covering all the regions of the weldments were metallographically etched to investigate the macro and microstructure. Macrostructure studies were carried out to examine the weld fusion with respect to the welding techniques and filler wires employed. Standard metallographic procedures were employed to examine the microstructure of the weldments. Electrolytic etching (10% oxalic acid - 10 V DC supply; 30 - 40 s; the current density of 1 A/cm2) process was employed to reveal the microstructure of the various zones of the weldments. The microstructural features were examined using the combined techniques of optical microscopy and an SEM equipped with EDS point analysis.

The data obtained from the microstructure studies were utilized to correlate the structure-property relationships. The results obtained from the various metallurgical examinations are outlined in detail in the following chapters.

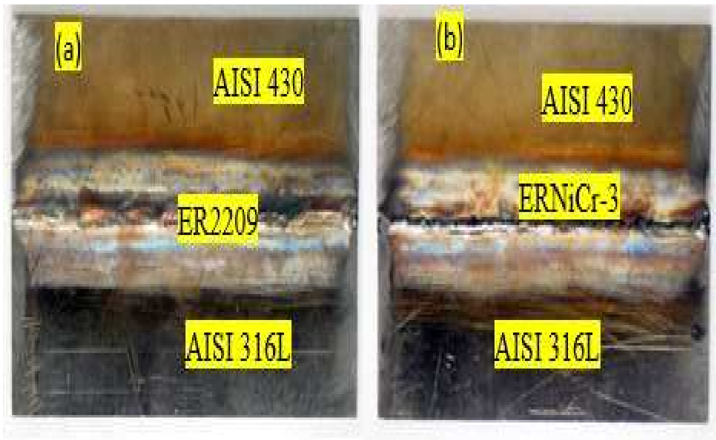

Figure 1: Dissimilar Weldment Images of AISI 430 and AISI 316L Employed by PCGTA Weld using: (a) ER2209 (b) ERNiCr-3 Fillers

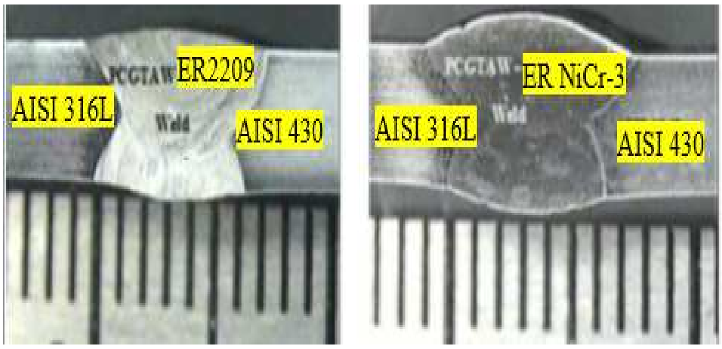

Figure 2: Macrostructure Images of Dissimilar Weldments of AISI 430 and AISI 316L Employed by PCGTA Weld using (a) ER2209; (b) ERNiCr-3 Fillers

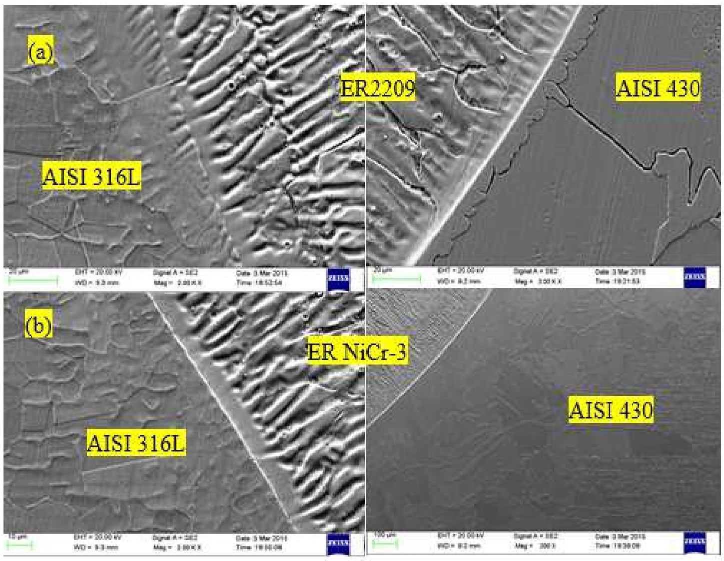

Figure 3: SEM Microstructural Images of Dissimilar Weldments of AISI 430 and AISI 316L Employed by PCGTA Weld using (a) ER2209; (b) ERNiCr-3 Fillers

3. RESULTS

3.1. Macrostructural Examination

The SEM photographs and macro-structure of PCGTA weldments of AISI430 and AISI 316L are depicted in Figure 1(a) & (b) and Figure 2(a) & (b). The results showed a proper weld bead with complete penetration of the base metals and filler metals in all the cases. Macrostructure examinations showed that narrow weld beads were obtained on employing PCGTA welding technique. It could also be inferred that the width of the fusion zone is found to be varying with respect to the filler wires and the welding techniques.

3.2. Microstructural Examinations

3.2.1. PCGTA Weldments by ERNiCr-3 Filler

Interface microstructures of the dissimilar combinations obtained from PCGTA welding techniques employing ERNiCr-3 are represented in Figure 4(b). The formation of secondary phases was well observed at the HAZ of AISI 430 weldments. However, the amount of segregation was found to be minimal for the PCGTA weldments. Grain coarsening effect was also being observed at the HAZ(s) of both the weldments. Moreover, the Migrated Grain Boundaries (MGBs) were distinctly observed at the weld zone of both weldments Figure 4(b). No solidification cracking was observed at the weld zone despite the presence of migrated grain boundaries. Also, it was inferred that the weld zone resulted in a complete austenitic weld due to the formation of MGBs at the weld zone.

3.2.2. PCGTA Weldments by ER 2209 Filler

Interfacial micrographs of PCGTA weldments employing ER2209 filler are represented in Figure 4(a). Grain coarsening has been vividly seen in the PCGTA weldments. Multi-directional grain growth such as the presence of cellular, columnar and dendritic growth was observed at this weld zone Figure 4(a).

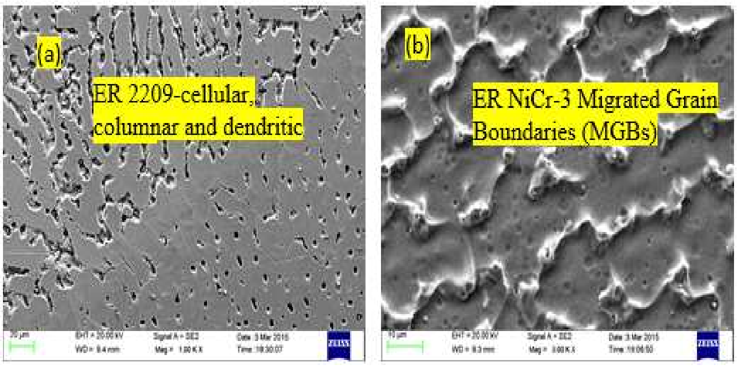

Figure 4: SEM Weld Microstructural Images of Dissimilar Weldments of AISI 430 and AISI 316L Employed by PCGTA Weld using a) ER2209; (b) ERNiCr-3 fillers

4. LINE SPOTTING ANALYSIS

4.1. PCGTA Weldments by ERNiCr-3 Filler

EDAX line mapping analysis was carried out on the weldments to infer the movement of elements and is represented in Figure 5. It was well inferred that the elemental migration was almost minimal and from AISI430 to weld zone Figure.5 PCGTA weldments. On the other hand, Fe has migrated from the HAZ of AISI 316L side to the weld zone; whereas Ni has migrated the weldments. Even though the content of Cr is almost equal in parent and filler metal,

slight variations occurred at the weld interface and the HAZ of AISI 316L Figure 5. On closer observation, it was found that Cr content has slightly lowered in the weld interface on PCGTA weldments.

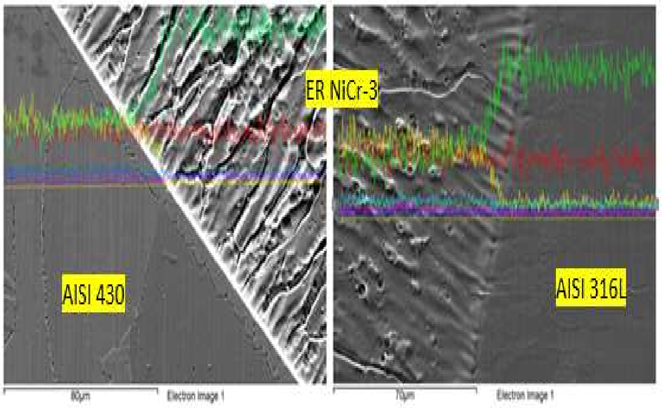

Figure 5: SEM Line Spotting EDS Analysis on Dissimilar Weldments Employed by ER NiCr-3 Filler PCGTA Weldments

4.2. PCGTA Weldments by ER2209 Filler

Line mapping analysis on PCGTA weldments employing ER2209 filler is represented in Figure 6. The results showed the migration of elements from HAZ of AISI 316L to the weld zone in this case Figure.6. It was also inferred that the weld zone has been enriched with Ni, Mo and Fe and these elements were dominated in Figure.6 PCGTA weldment. Tiny white phases were clustered at the HAZ of AISI 430 in case of PCGTA weldment.

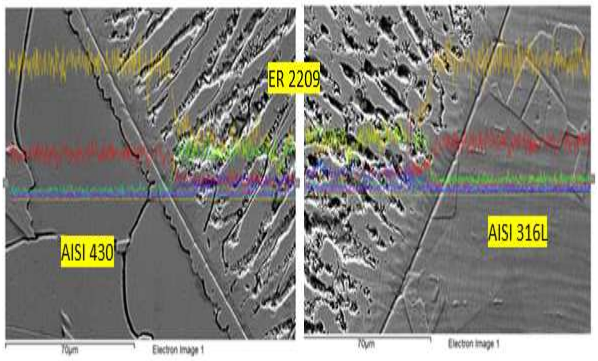

Figure 6: SEM Line Spotting EDS Analysis on Dissimilar Weldments Employed by ER2209 Filler using PCGTA Weldments

5. SEM/EDX ANALYSIS

5.1. PCGTA Weldments by ERNICR-3 Filler

SEM/EDAX point analysis was also carried out at the various zones of the weldments and is shown in (Figure.7). More specifically, the analyses were focused at the weld interface of both the metals. It was inferred that the secondary phases observed at the AISI 430 contained rich amounts of Ni, Fe, and Cr for this weldment (spectrum 32) (Figure.7). However, Nb and Mo content in the PCGTA weldments were found to be slightly low in weldments and HAZ of AISI 316L was observed to have some amounts of (spectrum 5) Cr, Ni, Fe, and Mo.

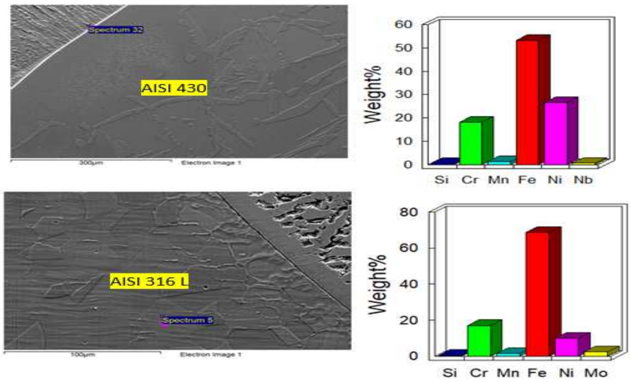

Figure 7: SEM/EDAX Analysis on Bimetal Weldments of AISI 430 and AISI 316L Employed by ERNiCr-3 PCGTA Weldments

5.2. PCGTA Weldments by ER2209 Filler

The point analysis on the ER2209 weldments showed the presence of Mn, Mo, Ni, and Cr along with other elements. In these weldments also, as discussed in the previous section, the Mo and Nb content appeared in the secondary phases were minimal in case of PCGTA weldments. The weld interface of AISI 430 both of these weldments (Figure.8). Showed higher amounts (spectrum 40) of Fe, Ni and Cr whereas Fe, Ni, and Cr dominated (spectrum 45) at the weld interface of AISI 316L (Figure.8).

6. DISCUSSIONS

The study outlines the investigation of the weldability, microstructural properties of AISI430 and AISI 316L using PCGTA welding technique and different filler wires. It is well inferred from the macrostructure studies that the dissimilar welds obtained from PCGTA welding technique were found to be free from any macroscopic defects. Further, the gamma-ray NDT inspection technique also confirmed the absence of weld defects such as porosity, undercuts, inclusions etc. in all the weldments. A closer view of the macrostructure depicted the formation of narrow beads on employing PCGTA welding technique for both filler wires.

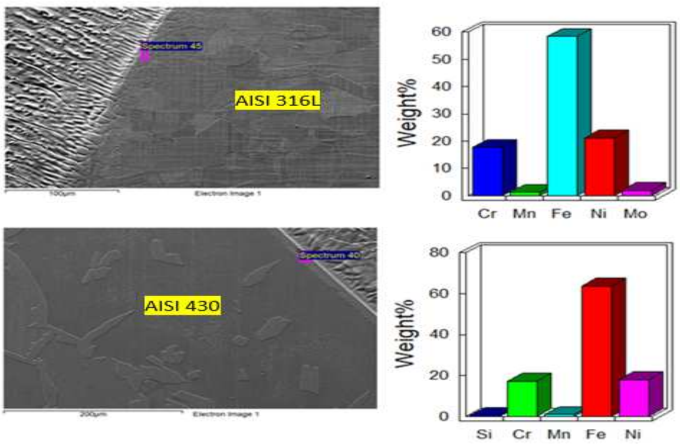

Figure 8: SEM/EDAX Analysis on bi-Metal Weldments of AISI 430 and AISI 316L Employed by ER2209 PCGTA Weldments

This could be reasoned out because of the controlled heat input developed during the PCGTA welding process [15-18]. Microstructure examination clearly divulged the formation of secondary phases at the HAZ of AISI 430 in

PCGTA weldments employing ERNiCr-3. However, the number of secondary phases present in PCGTA weldments was found to be minimal. These secondary phases appeared as tiny white precipitates were inferred to be precipitates richer in Nb and Mo. These phases could be well established from the SEM/EDAX line mapping analysis in such a way that the Nb and Mo content found in the secondary phases were found to be minimal for PCGTA weldments. The lower amounts of Nb and Mo also indicated that these elements were dissolved in the matrix to the extent possible and remaining elements segregated as secondary phases. From this, it is vividly concluded that PCGTA weldments resulted in lower segregation weldments.

Migrated grain boundaries (MGBs) could be prominently seen in the weld zones employing ERNiCr-3 filler. MGBs are prevalent in the fully austenitic welds and migration of the boundary is possible during reheating, such as during multi-pass welding [10]. Moreover, the presence of higher amounts of Ni in the weld zones employing ERNiCr-3 clearly stated that the mode of solidification would be completely austenitic. The presence of Nb constituent in the filler wire also stabilizes the austenitic matrix Also it was stated that MGBs normally resulted in ductility dip cracking (DDC) in the welded structures. As the filler wire consisted of higher amounts of Cr, it combated the DDC problem as evident from the microstructure. It could be seen that the filler wire chosen for the study was found to be reasonable for joining these metals.

Microstructures of ER2209 weldments showed the controlled heat input generated during PCGTA welding, the coarsened grains were addressed very minimally. Also, it could be envisaged from the weld microstructure that the weld zone witnessed multi-directional grain growth. Except for the presence of Mo and N, the major elements present in the composition of the ER2209 filler metal were Fe, Cr, and Ni those have lower tendency to segregate in the inter-dendritic and inter-granular regions. Hence, there is a minimal driving force to change the solidification mode from cellular to dendritic. Similar observations were reported by Shah Hosseini et al. [9]. Moreover, the presence of delta ferrite stringers was evident at the HAZ of AISI 316L for all the weldments. It was reported that the delta ferrite stringers control the grain growth and minimize the susceptibility to HAZ liquation cracking [4, 10, and 19].

It is difficult to arrive at a conclusion to recommend the suitable welding technique and filler wire for joining these bimetallic joints. However, it was accrued from the study that the weld strength was found to be greater than one of the parent metal i.e. AISI 316L. This could be well explained with the microstructures such that the presence of ferrite stringers at the HAZ region was observed after these welding trials. Moreover, researchers addressed that the enhanced weld properties could be achieved by having the optimal ferrite count. It is well elucidated from these studies that the selection of process parameters and filler wires for joining these bimetals provided pensive results.

The objective of the present study is to obtain successful dissimilar weldments of AISI430 and AISI 316L. The metallurgical studies have been determined carefully to interpret the structure-property relationships. The outcomes of the study will be a tribute to the paper and pulp industries employing these bimetallic combinations.

7. CONCLUSIONS

This study aimed to investigate the weldability and structure-property relationships of the dissimilar combinations of AISI 430 and AISI 316L using Pulsed Current GTA welding technique by employing ER2209 and ER-NiCr-3 fillers. The outcomes of the study are summarized as follows:

- Successful dissimilar joints of AISI 430 and AISI 316L could be achieved by PCGTA welding techniques using these filler wires.
- Microstructure studies showed the presence of secondary phases at the HAZ of AISI 430 for the weldment employing ERNiCr-3; however, these phases were found to be minimal for PCGTA weldment. Weld microstructures exhibited the formation of migrated grain boundaries on employing ERNiCr-3 however without the ductility-dip cracking. This tendency was achieved due to the presence of Nb in the filler.
- Based on the metallurgical property investigations, the present study recommends the use of pulsing current GTA welding technique and ERNiCr-3 filler were suitable for joining these bi-metallic combinations.

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